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Problems Associated With the Assessment of Local Site Effects Through a Multidisciplinary Integrated Study: The Case of Fivizzano's Town (Italy)

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PROBLEMS ASSOCIATED WITH THE ASSESSMENT OF LOCAL SITE EFFECTS THROUGH A MULTIDISCIPLINARY INTEGRATED STUDY: THE CASE OF FIVIZZANO'S TOWN (ITALY)

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ABSTRACT

The evaluation of local site effects, by means of ground response analyses, is a very complex and difficult task, which requires a multidisciplinary approach. This is operative philosophy expressed by VEL Project (*Valutazione degli Effetti Locali*), sponsored by Tuscany Region, to the aim to seismic risk characterization in the main seismic areas (i.e. Garfagnana, Lunigiana, Amiata, Valtiberina and Mugello). One of the most important urban centres, involved in the multidisciplinary activity of the VEL project, is certainly the town of *Fivizzano* located nearby the city of Massa, which was strongly damaged during the earthquake of September 1920 (the strongest seismic event occurred in Northern Apennines in the latest centuries).
Remarkably good macroseismic information is available about the destructive impact yielded at *Fivizzano* by this earthquake (e.g. number of casualties, level of damage of buildings, etc). The main objective of this paper is to identify the occurrence of possible local site effects in the *Fivizzano*'s area following the 1920 earthquake and to quantify them by means of one and two-dimensional site response analysis. The input data required for study were obtained through a comprehensive geological survey and a multi disciplinary underground exploration of the area.

INTRODUCTION

The assessment of local site effects within the framework of seismic microzonation constitutes a difficult task to be carried out. According to the current trends three are the main approaches that one may follows: qualitative (G.N.D.T. – C.N.R., 1986; CNR-GNDT, 1997; D'Amico et al., 2000), simplified (Medvedev, 1965; Broili, 1979; Nakamura, 1989) and analytic methods (Celebi, 1995; Bellucci et al., 1998; Pergalani et al., 1999; Ferrini et al. 2001; D'Intinosante, 2003; Signanini et al., 2003).
The approach used in the VEL Project is that of analytical methods. The latter is a regional research project aimed to assess local site effects in the Tuscany region, Italy, and it has been sponsored by the local administrators of Tuscany Region within the frame-work of the regional law "Seismic Risk Hazard Reduction with Experimental Interventions" number 56 of 30.07.1997.
More specifically, the scope of the VEL project is the identification through a series of ground response analyses conducted for a given earthquake scenario within the borders of a prescribed territory (mainly concentrated in little towns and villages), areas of homogeneous behaviour from the standpoint of site amplification. The results of this study whose implementation necessarily requires a multidisciplinary approach, will be subsequently used by the administrators of Tuscany Region for seismic microzonation so to identify the areas (especially within major urban centres and communication infrastructures) where local site effects are expected in case of future earthquakes. In this context a

seismic amplification study was initiated in 2001 in the area of Fivizzano that was strongly damaged during the 1920 earthquake.
The choice of Fivizzano as the site selected for the pilot study has been motivated by two reasons: the first is that the September 1920 earthquake has been the strongest seismic event occurred in Northern Apennines in the latest centuries. The second is the availability of well-documented, high-quality macroseismic information, in particular concerning the geographic distribution of damage on buildings and on the constructed environment in general. This even though strong-motion quantitative information for this event is unavailable due to inadequate seismic instrumentation used at that time.
The macroseismic, qualitative information retrieved from the historical records allowed a comparison of these data with the results of a series of numerical simulations performed using one and two-dimensional site response analyses. The input data required for these analyses were obtained through a multi-disciplinary geological, geophysical and geotechnical investigation campaign.

Table 1. Main seismic events in Fivizzano's area from 1481:. I_{LOC} = site macroseismic intensity, I_{MAX} = maximum epicentral intensity. From Boschi et al., 2000.

DATE	TIME	LAT	LONG	I_{LOC}	I_{MAX}	EPICENTRAL AREA
07/05/1481	14:15	44.27	10:13	8.0	8.0	Garfagnana
21/01/1767	07:45	44.13	10.12	8.0	8.0	Fivizzano
21/01/1767	09:00	44.23	10.12	6.5	6.5	Fivizzano
11/04/1837	17:00	44.18	10.18	7.0	10.0	Alpi Apuane
25/02/1904	18:47	44.48	10.63	5.0	7.0	Reggiano
06/10/1904	11:15	44.20	10.82	5.0	7.0	Frignano
25/08/1909	00:22	43.13	11.33	0.0	8.0	Southern Tuscany
13/01/1915	06:52	41.98	13.65	0.0	11.0	Marsica
29/06/1919	15:06	43.95	11.48	3.0	10.0	Mugello
07/09/1920	05:55	44.:18	10.28	9.0	10.0	Garfagnana
11/09/1983	16:29	44.77	10.27	4.0	7.0	Parmense

HYSTORICAL ANALYSIS

The district of Fivizzano, in its ancient history, has been affected by numerous earthquakes. The most significant events in terms of macroseismic intensity scale are listed in Table 1 (Boschi et al., 2000). The September 7, 1920 earthquake is by far the most severe seismic event occurred in Northern Tuscany in recent times.
The main shock struck at about 5:55 a.m. Greenwich time (Tosatti, 1922) and had a duration of approximately 20 seconds (De Stefani, 1920). It was preceded by a series of minor shocks the greater of which occurred at 2:05 p.m. of the previous day. The earthquake caused 171 victims and about 650 injured people. Thousands were the homeless (AA.VV., 1987).
Figure 1 shows three maps of isoseisms (Iaccarino, 1968 in Fig.1a, Eva et al., 1978 in Fig.1b, and AA.VV., 1985 in Fig.1c) reporting the effects on the territory of the September 1920 earthquake. Despite the three macroseismic models show a rather conflicting areal distribution of macroseismic intensity, all three maps agree on displaying that the Fivizzano's area has been one of the most badly struck by the earthquake.

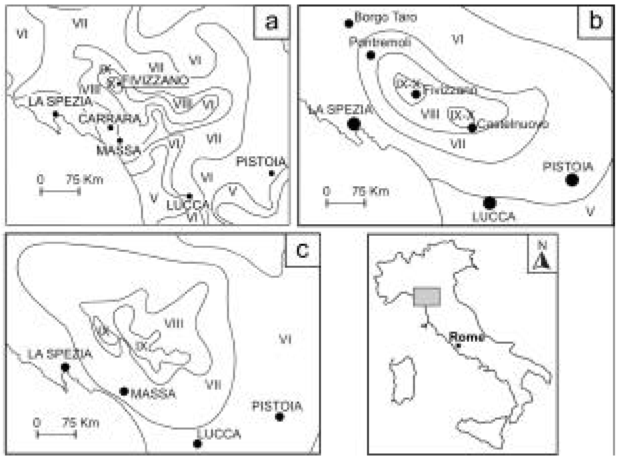

Fig. 1.Isoseismal maps related to the September 1920's earthquake: a) Eva et al., 1978; b) Iaccarino, 1968; c) AA.VV, 1985.

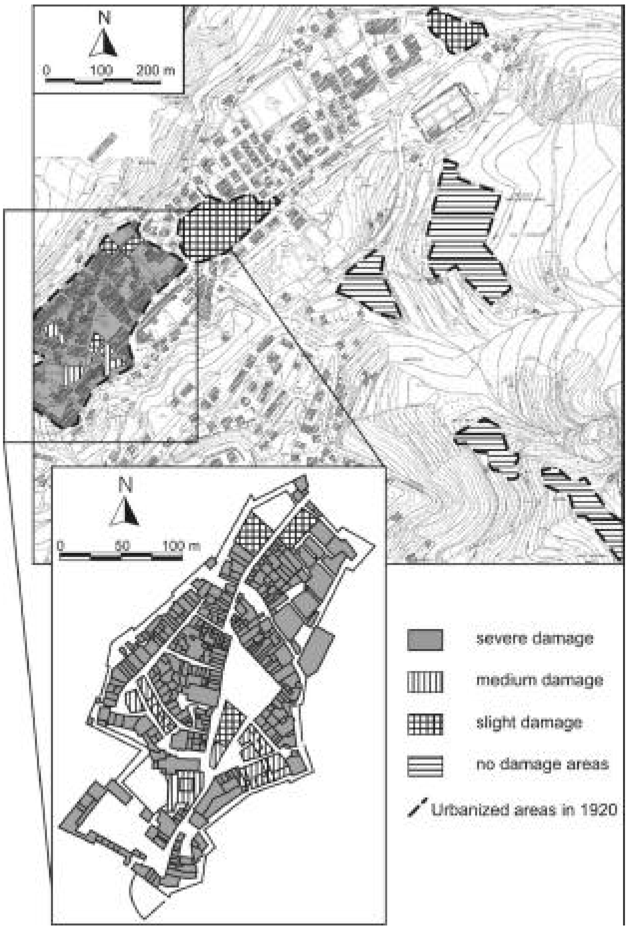

Fig. 2. Map of the damage on buildings at the historical site of Fivizzano, related to the 1920's earthquake.

As a matter of fact, Fivizzano was severely hit by the 1920 earthquake both for the number of casualties and for the extent of damage to the historical and cultural building heritage. As shown in Fig. 2, almost all the houses of the historical centre of Fivizzano (located in the southern part of the fluvial terrace) have experienced during the earthquake some kind of structural damage. Most of these buildings were demolished during the successive phase of reconstruction, while for the others were put in place robust measures of structural retrofitting (like for instance by reducing the number of stories of multilevel buildings, particularly for the houses placed in the southern part of the town). It is interesting to note however that the heavily populated areas located in the eastern sector of the city which lie on outcropping bedrock formations, have suffered far less severe effects from the earthquake. This difference in the level of damage in different parts of the city is attributed to the presence of fairly thick layers of alluvial covering deposits that caused strong local site effects in the southern part of the city, particularly at the site of location of the fluvial terrace where there is a good correspondence between maximum layer thickness and more heavily damaged areas.

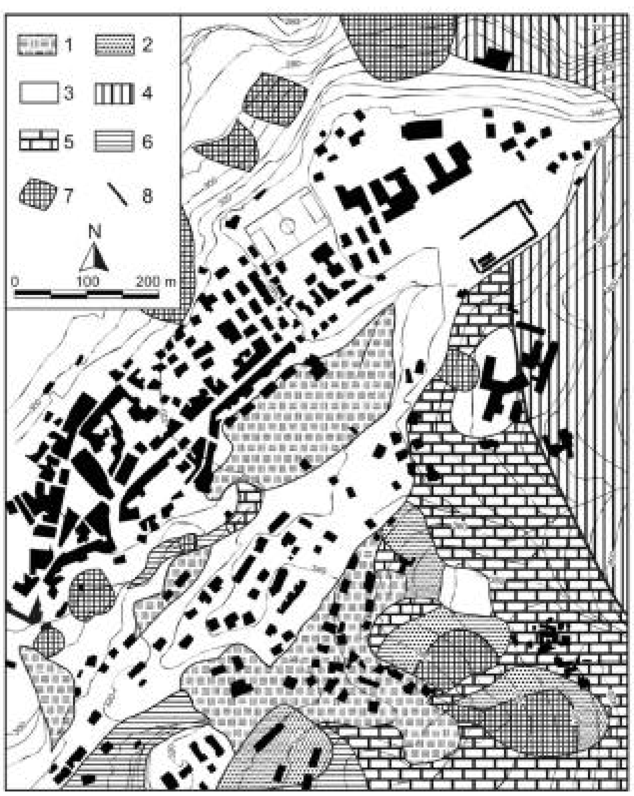

Fig. 3. Simplified geological map of Fivizzano, Tuscany: 1) fill (Holocene), 2) detrital deposits (Holocene), 3) alluvial deposits (Holocene), 4) "Macigno" formation (Upper Oligocene Lower Miocene), 5) "Groppo del Vescovo" limestones (Lower Eocene), 6) "Argille e Calcari" formation (Upper Cretaceous - Middle Eocene), 7) landslide, 8) fault.

GEOLOGICAL CHARACTERISTICS

Most of Fivizzano's town is placed on a terrace alluvium on the left of the hydro-graphic Rosaro stream which is the most important river of the area. Figure 3 shows a geological plan of Fivizzano's centre.

The southern portion of the area is characterized by a substratum constituted by the Canetolo's Unit: "Argille e Calcari" formation (Upper Cretaceous - Middle Eocene) and the "Groppo del Vescovo" limestone (Lower Eocene) which is outcropping on the eastern part of the area. These lithotypes are in a tectonic contact (via an important structural element on a regional scale) with the "Macigno" sandstone (Tuscany non-metamorphic formation) cropping up in the north-eastern sector. The Quaternary coverings are formed by reclaimed lands, refilled grounds, detrital deposits and terraced alluvial deposits. Another feature that one may observe in the most sheer zones of the area is the presence of some active and dormant gravity phenomena.

UNDERGROUND EXPLORATION

After completing the geological survey of the area, a multidisciplinary subsoil exploration campaign was undertaken (see Fig. 4) with the purpose to define the physical-mechanical parameters of the lithotypes that characterize the formations underlying the town of *Fivizzano* as well as to provide some information about the underground body geometry. The geophysical-geotechnical investigation campaign has comprised:

- 3 boreholes;
- 19 refraction surveys for P and SH waves;
- 2 down-hole seismic tests for P and SH waves.

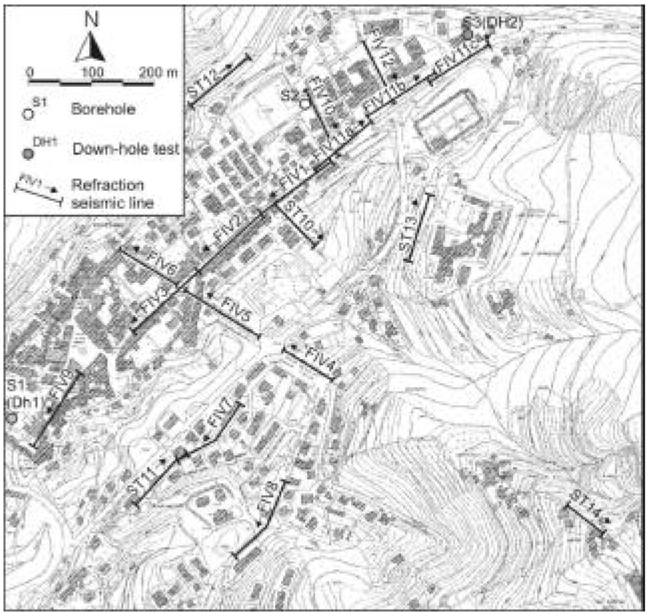

Fig. 4. Location of the geophysical-geotechnical investigation campaign conducted in Fivizzano's area.

On the basis of the acquired data it was possible to construct an isopach map of the formations characterized by Vs<800 m/sec (see Fig. 5). From this it is possible to estimate how the thickness of such formations (chiefly terraced alluvial deposits of the Rosaro stream) is gradually decreasing in east direction. The minimum values are found in the eastern area and next to the Concia trench where the substratum is outcropping. Finally Fig. 5 shows that the highest values of thickness of the alluvial deposits (about 40 meters) are those associated with the formations placed on the northern sector of the alluvial terrace. One of the outcomes of this multidisciplinary subsoil investigation campaign was the construction of a couple of simplified geological-technical sections illustrated in Fig. 6 which have been particularly useful in carrying out two-dimensional site response analyses.

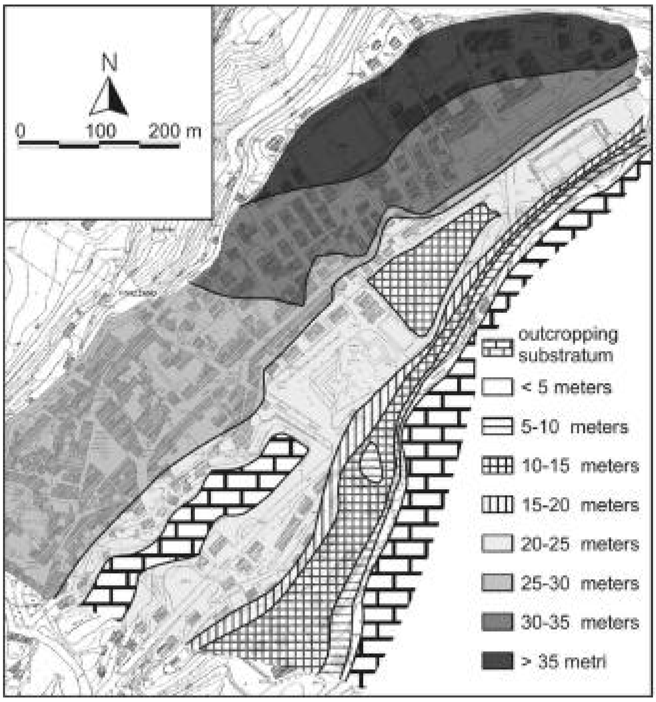

Fig. 5. Isopach map of litotypes characterized by Vs<800 m/sec in Fivizzano's area.

ONE AND TWO-DIMENSIONAL SIMULATIONS

The sections built by means of geological surveys and geophysical test interpretation must be transformed into physical-mathematical models that can then be solved using appropriate numerical codes. The modeling activity for one and two-dimensional simulations follows different criteria. These criteria relate to specific assumptions with regards to the geometry, kinematics as well as the algorithms used to solve the problem.
One-dimensional simulations by means of ProShake code (EduPro Civil System Inc., 1996) employ transferring functions carried out over boundaries between layers. This approach follows the hypotheses listed below:

1. Only SH wave propagation is dealt with;
2. Direction of the SH wave propagation is vertical;
3. Layers lay horizontally;
4. The soil constitutive behavior under earthquake loading is linear equivalent of viscoelastic type;
5. The bedrock is accounted for as an elastic and semi-infinite continuum.

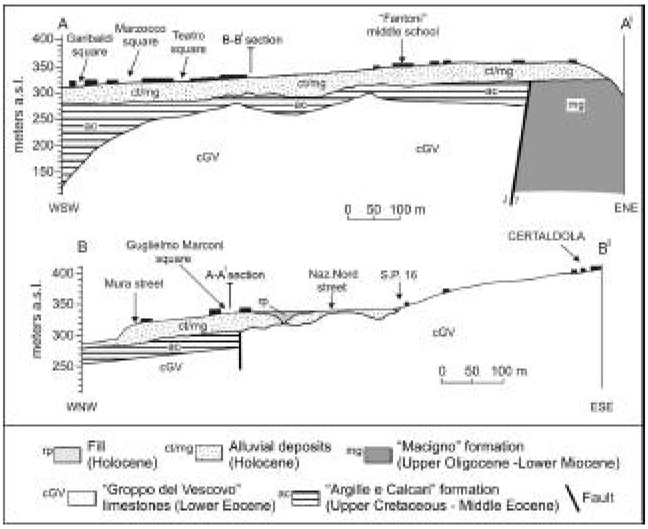

Fig. 6. Geological sections used for two-dimensional site response analyses.

The limit of eligibility of one-dimensional simulation is that it cannot take into account effects of both superficial and embedded geometry. This latter can heavily influence the local amplification or deamplification effects induced by waves propagation. Consequently one-dimensional analyses reveal the effects of layer sequences within investigated sections and present no implementing difficulties such as two-dimensional analyses.
On the other hand two-dimensional dynamic finite element simulations, carried out by means of QUAD4M (Hudson M.B. et al., 1993), allow to assess the influence of geometry and mechanical characteristics of soils under the following hypotheses:

1. Only SH wave propagation is taken into account;
2. The soil constitutive behavior under earthquake loading is linear equivalent of viscoelastic type;
3. The bedrock is accounted for as an elastic and semi-infinite continuum.

This enhanced simulation – with respect to the one-dimensional simulation – needs more details in the definition of the layer geometry from geological sections and more advanced expertise in the modeling activities. For the two-dimensional simulation in Fivizzano village two sections are investigated along two main directions as Fig. 7 shows. The material types of soils and the two sections have been illustrate in Fig. 6.
Section AA lays along the direction of development of the ancient and the modern part of the village. Section BB is almost orthogonal to the previous section. The analyses of the

two sections provide approximately an estimation of local site effects in different geometrical conditions.

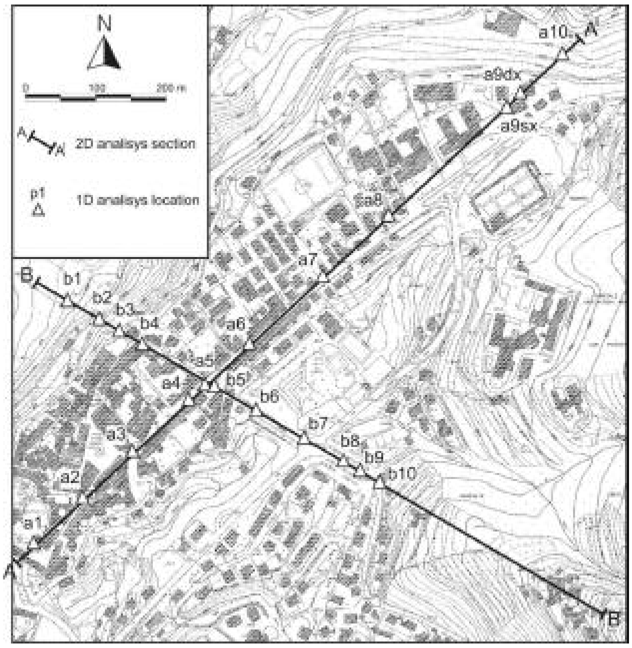

Fig. 7. Location of surface receivers for dynamic ground response carried out using one-dimensional analysis along the two sections of two-dimensional model.

To perform the two-dimensional simulations, after constructing the model from geological sections it is necessary to define the following pieces of information:

- the distance of the cutoff lateral boundaries for which they don't affect results recorded in the region under study;
- the dimension of the elements considering that they must respect the following dynamic compatibility condition:

$$d \le \frac{l_{\min}}{K} = \frac{V_s}{K \cdot f_{\max}} \qquad (1)$$

where Vs is the shear wave velocity of the soil; K is the stability coefficient whose value is taken equal to 7 (Lanzo G. and Silvestri F., 1999) and f_{max} is the maximum frequency of the input signal that one wish to propagate.
The results of the preliminary stage of the model refinement are:

- the distance of the cutoff lateral boundaries is taken equal to 200m;
- the length of the elements is 8m for alluvial deposits and 11m for "argilla e calcari" formation;
- the bedrock material used in the two sections is cGV. The presence of mg in the section AA can be neglected because its mechanical properties are similar to the cGV and don't affect the results recorded at the surface.

One-dimensional analyses have been conducted along section AA' and section BB' and the results were computed at 10 location for each section (see Fig. 7). These positions were selected in order to calculate ground response corresponding to most significant zones for amplification effects along the sections, as the top of the slope, the middle of the alluvial valley, etc (Aki K. and Larner K.L., 1970; Bard P.Y., 1982). The same locations are better illustrated in Fig. 8 and Fig. 9. Along section AA and section BB were constructed one-dimensional sections, named by means of the letters of the corresponding section. Nodes of the finite element meshes are showed in the same figures.

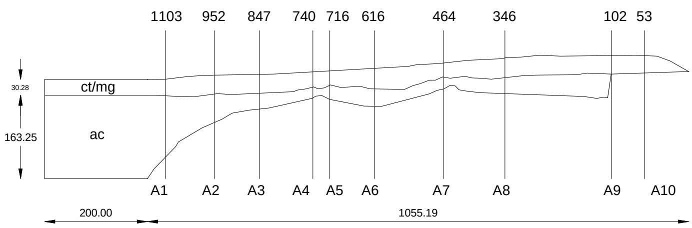

Fig. 8. Locations of surface receivers to monitor dynamic response at section AA for one-dimensional analysis – beginning with A on the bottom- and two-dimensional analyses – number of nodes at the top.

The results of the two-dimensional analyses, in terms of acceleration spectra and amplification factors, are computed at the nodes whose abscissa is the nearest to the one-dimensional section chosen for the analysis. This will allow to compare the results obtained with 1D and 2D analyses and to make remarks on the differences between the two approaches.
For each one-dimensional analysis the physical and mechanical properties that have been used were the soil unit weight ã, the initial shear modulus Gmax, and the Poisson ratio õ. These last two parameters were drawn from the measurements of Vs and Vp obtained from the seismic refraction tests.

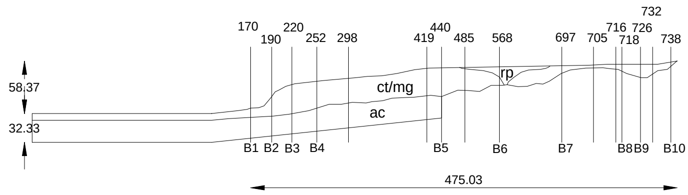

Fig. 9. Locations of surface receivers to monitor dynamic response for section BB for one-dimensional analysis – with B on the bottom- and two-dimensional analyses – number of nodes on the top.

Values of Vp and Vs used in one-dimensional sections relate to local measurements from seismic refraction tests. These local measurements have been used into two-dimensional simulation, too. No averaging operation was carried out neither in one-dimensional nor in two-dimensional simulations. Local values of soil properties were used in order to represent the heterogeneous nature of the formations without using any stochastic treatment of the data.

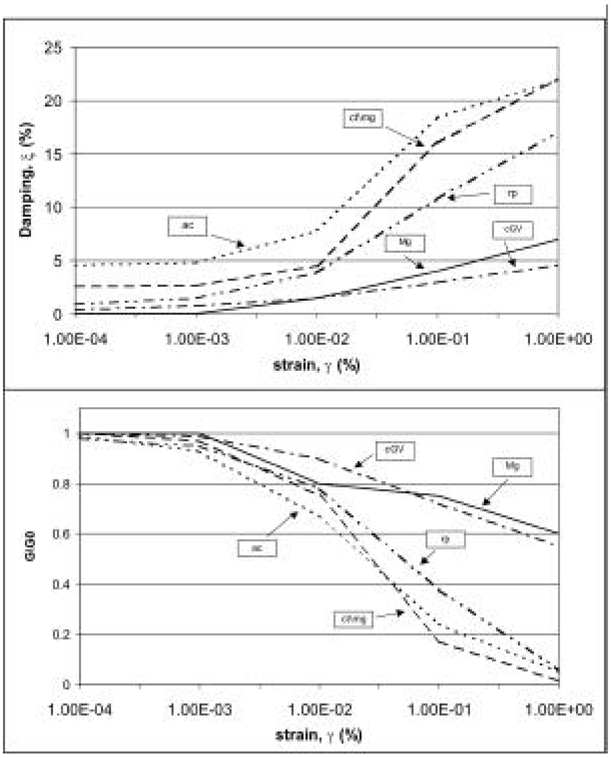

Fig. 10. Shear modulus and damping ratio degradation curves used for one and two dimensional site response analyses.

Both types of analyses implement linear equivalent viscoelastic soil constitutive behavior through the shear modulus and damping ratio degradation curves shown in Fig. 10. These curves were calculated within the VEL project from Petrini et al., 2000 and Ferrini et al., 2001.

With regards the design earthquake applied to both 1D and 2D simulations no recorded accelerogram was available for Fivizzano.

Accordingly a synthetic time-history accelerogram was used (see Fig. 11) which was obtained by combining the macroseismic information available for the 1920 September earthquake with the Italian strong-motion database using a stochastic approach.

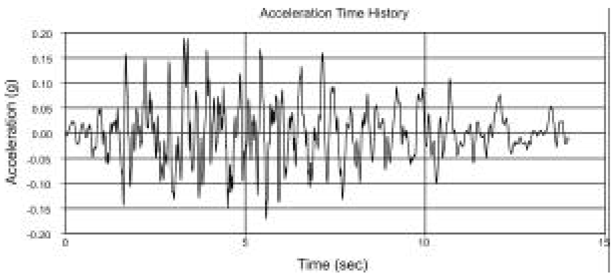

Fig. 11. Input motion used for one and two dimensional site response analyses.

The peak ground acceleration used for the analysis is the value obtained from the Italian strong-motion database for Fivizzano village, that is 0.0189g. Acceleration spectra of one and two-dimensional simulations are shown in Fig. 12-13 and Fig. 14-15 respectively for section AA e section BB.

It is apparent from these charts that the amplification period for the one-dimensional profiles along section AA ranges in the interval 0.3÷0.45 sec (2.2÷3.3 Hz) whereas along section BB the interval is shifted of 0.2÷0.4 sec (2.5÷5 Hz). By comparing the one–dimensional and the two-dimensional simulations along the two sections one can notice that for the section AA the amplification periods range to the wider range of 0.3÷1.0 sec (1÷3.3 Hz) with the highest amplification at 0.5 sec (2 Hz).

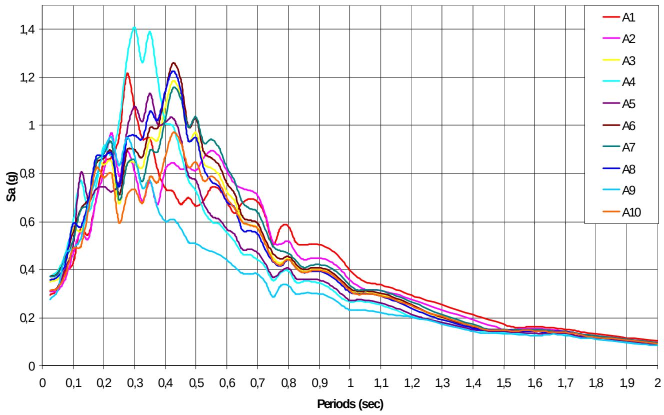

Fig. 12. Acceleration spectra from one-dimensional analyses along section AA.

Section BB in Fig. 15 exhibits the highest amplification which occurs at 0.5 sec while the amplification period ranges in the interval 0.2÷0.5 sec (2÷5 Hz). These results imply that the local site effects of soil deposits in section AA are lighter than those associated with section BB.

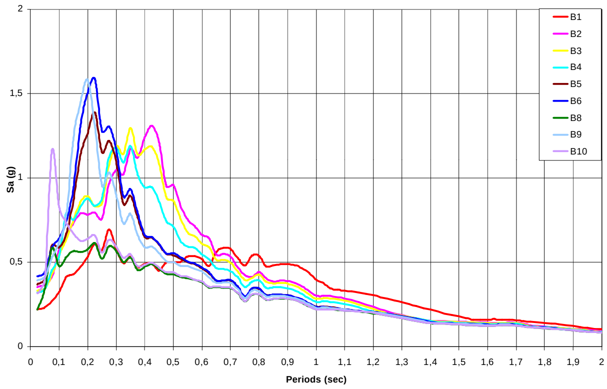

Fig. 13. Acceleration spectra from one-dimensional analyses along section BB.

The higher values of stiffness of section BB yield in one-dimensional analyses a shift of the amplification periods towards lower values. However these 1D analyses show the same range of amplification period in both section AA and section BB therefore they are not able to capture the almost doubled extension of the amplification period in section AA.

Differences among the results of one and two-dimensional site response analyses are quantified by the amplification factors

calculated according to the Housner (1956) formulation. In the latter the factor is calculated as the ratio between the response spectral intensity and the input motion spectral intensity in the period ranges of 0.1÷0.5 sec and 0.1÷2.5 sec respectively.
The amplification factors obtained from one and two-dimensional simulations are compared in
Fig. *16* and Fig. 17 for section AA and section BB respectively. According to the amplification factors computed along section AA two-dimensional simulations give higher values of site amplification than one-dimensional analyses. This is also true for section BB.

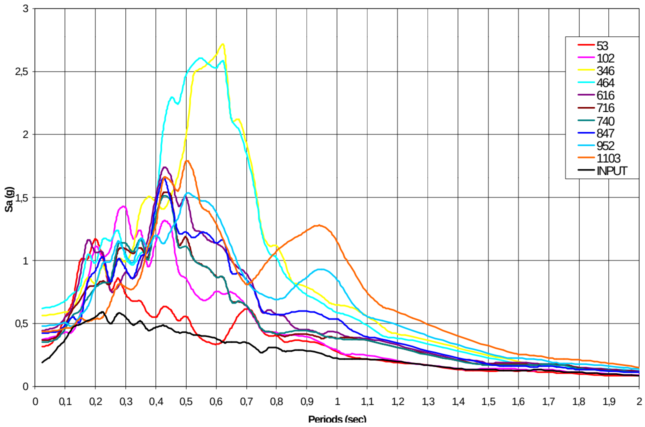

Fig. 14. Acceleration spectra from two-dimensional analyses along section AA.

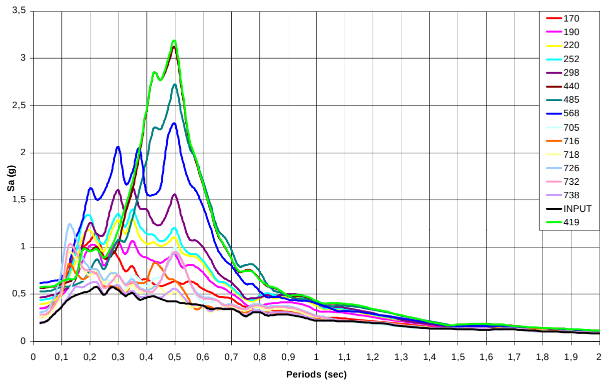

Fig. 15. Acceleration spectra from two-dimensional analyses along section BB.

Differences in the amplification factors show that the influence of geometry may be important and one-dimensional site response analyses are unable to account for it. The effects of impedance contrast at the layer interface which is captured by one-dimensional simulations, weights just only 50% of all the amplification factor. The more the layers are horizontal and the geometry is symmetrical the less important are the geometry effects.
As a matter of fact let consider the points where the amplification factors and the acceleration spectra are the highest for section AA. They are denoted as points 346-A8, 464-A7, 616-A6, 952-A2 and 1103-A1. As shown in Fig. 8, all these locations are characterized by an evident asymmetry and for point 464-A7 there is also an embedded hill which is responsible for the high value of amplification. At points 1103-A1 and 952-A2 the softer layers steeply increase their embedment.

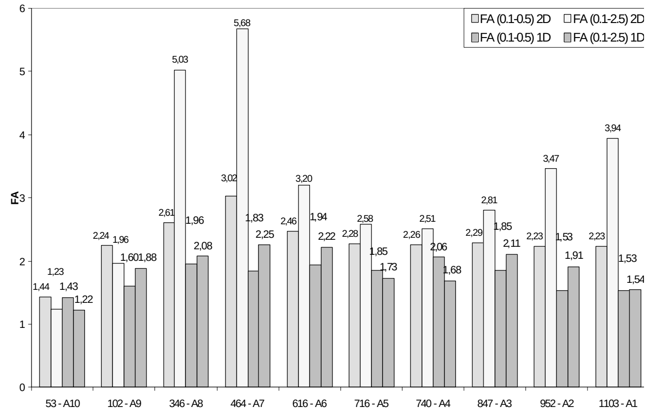

Fig. 16. Amplification factors along section AA registered for one and two-dimensional simulations.

On the contrary, points 102-A9 and 53-A10 show lower values of amplification factors which can be explained with a little and horizontal position of the superficial soft soil layer. The same considerations can be done for section BB. The highest amplification factors are recorded at locations 568-B6, 440-B5, 252-B4 and 220-B3. The point 568-B6 is on the softest soil layer with a particular geometry.
The location 440-B5, which has the highest amplification factor, joins together the effects of a 80m depth of soft soil and asymmetric geometry, as can be seen in Fig. 9. The other three locations suffer the typical amplification effects of a slope geometry. All of these topographic effects are completely neglected by the one-dimensional analyses.

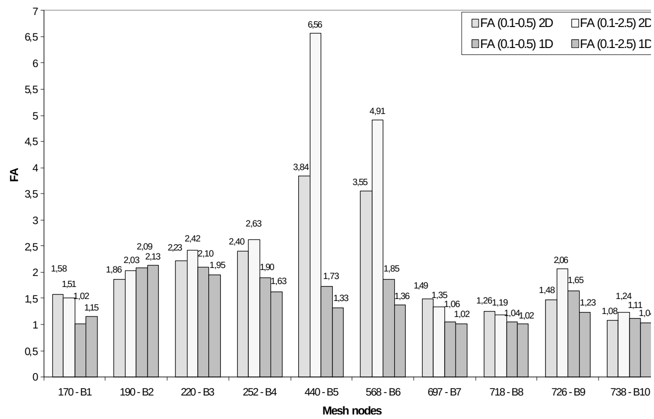

Fig. 17. Amplification factors along section BB registered for one and two-dimensional simulations.

On the contrary, points 102-A9 and 53-A10 show lower values of the amplification factors, a fact that may be explained with the little thickness and the sub-horizontal position of the superficial soft soil layer. The same considerations apply for section BB. The highest amplification

factors are computed at points 568-B6, 440-B5, 252-B4 and 220-B3. Point 568-B6 is on the softest soil layer with a particular geometry. Point 440-B5 is characterized by the highest amplification factor since it combines together the effects of a 80m depth soft soil layer and an asymmetric geometry, as shown in Fig. 9. The remaining three points suffer the typical amplification effects of a slope geometry. Obviously all these topographic effects cannot be reproduced by one-dimensional analyses.
Finally at points 726-B9, 738-B10 and 190-B2 the differences in the amplification factors between 1D and 2D analyses are reduced. This result is due to the minor effect of geometry upon the amplification caused by the impedance contrast at the interface.

COMPARISON WITH DESIGN SPECTRA PRESCRIBED BY THE ITALIAN BUILDING CODE

The design spectra specified by the Italian building code have been compared with the acceleration spectra computed in this study in two-dimensional analyses (see Fig. 12-Fig. 15). The latter are normalized with respect to the initial value of the design spectra prescribed by the new Italian code (Ord. 3274 effective from 20 March 2003). The design spectra are of three types corresponding to three kind of local conditions identified through the dynamic properties of the first 30m depth soil profile.
Consequently, the one-dimensional soil profiles corresponding to the nodes of the two-dimensional analyses have been assessed, by means of expressions from the Italian code, so to identify the soil category they belong to. This work has been done for both section AA and section BB. The result was that all of the locations studied along sections AA and BB belong to the soil category named B.

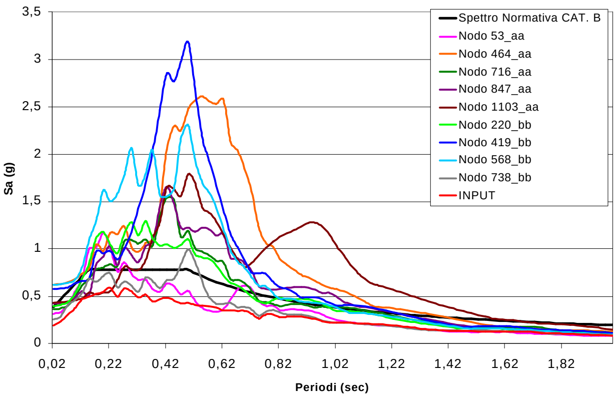

Fig. 18. Comparison amongst acceleration spectra recorded from two-dimensional analyses in Fivizzano town and the design acceleration spectrum from the Italian building code.

This category is characterized by the acceleration spectrum shown in Fig. 18 which was plotted together with the normalized acceleration spectra computed in this study. This comparison shows that the design spectrum from the Italian building code doesn't applies well to Fivizzano town because it underestimate the amplification site effect and the amplitude of the range of period involved in the amplification phenomenon. In fact the range of periods extends from 0.2 sec to 1.0 sec (1.0 to 5 Hz).
As a result of this study it is possible to say that when the soft soil layers have a depth greater than 30m and the local topography and embedded geometry are characterized by certain abrupt asymmetries (e.g. layers are not horizontal), local site effects must be ascertained through 2d ground response analyses.

DISCUSSION

The assessment of local site effects in studies of seismic microzonation is still an open issue since it may be tackled following different approaches and methodologies.
The objective of this paper was to study the characteristics of local seismic amplification at the site of *Fivizzano* in Tuscany, through a multidisciplinary and analytic approach. In particular, after the acquisition of the geological data by means of shallow surveys, a multidisciplinary subsoil investigation campaign has been carried out with the purpose of defining the physical and geomechanical parameters of the formations underlying the site under study and providing useful data about the underground body geometry.
This geological-geotechnical characterization of the site was fundamental for the definition of the input parameters to be used in one and two-dimensional site response analyses.The results obtained from the numerical simulations seem to quantitatively confirm the qualitative-type of information retrieved from the historical records about the macroseismic after-effects of the 1920 earthquake.
A cross-checking of the historical data with the outcome of the analyses confirmed that the most heavily damaged areas (located not only in the *Fivizzano*'s district, but also in certain areas of *Garfagnana* and *Lunigiana*) were those placed on that parts of the town characterized by a thickness of unconsolidated soil deposits (constituted mainly by alluvial, detrital or morainic lithotypes) ranging from 20 to 50 meters.
A future step forward of this research will be to carry out other site response analyses using different types of input motion with the purpose to a) better study the local site effect on seismic amplification and b) to assess the influence in Fivizzano's area of possible differences in the spectral characteristics of ground motion between today and several years ago.

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